# New constraints on European glacial freshwater releases to the North Atlantic Ocean

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# New constraints on European glacial freshwater releases to the North Atlantic Ocean

Frédérique Eynaud,[1] Bruno Malaizé,[1] Sébastien Zaragosi,[1] Anne de Vernal,[2] James Scourse,[3] Claude Pujol,[1] Elsa Cortijo,[4] Francis E. Grousset,[1] Aurélie Penaud,[5] Samuel Toucanne,[6] Jean-Louis Turon,[1] and Gérard Auffret[6]

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[1] During the late Quaternary, both external and internal forcings have driven major climatic shifts from glacial to interglacial conditions. Nonlinear climatic steps characterized the transitions leading to these extrema, with intermediate excursions particularly well expressed in the dynamics of the Northern Hemisphere cryosphere. Here we document the impact of these dynamics on the north-eastern North Atlantic Ocean, focussing on the 35–10 ka interval. Sea-surface salinities have been reconstructed quantitatively based on two independent methods from core MD95-2002, recovered from the northern Bay of Biscay adjacent to the axis of the Manche paleoriver outlet and thus in connection with proximal European ice sheets and glaciers. Quantitative reconstructions deriving from dinocyst and planktonic foraminiferal analyses have been combined within a robust chronology to assess the amplitude and timing of hydrological changes in this region. Our study evidences strong pulsed freshwater discharges which may have impacted the North Atlantic Meridional Overturning Circulation.
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## 1. Introduction

[2] Quantification of past sea-surface conditions is a challenge in paleoceanography [e.g., *MARGO Project Members*, 2009]. Several methods, based on a large array of proxies, now exist, though many provide contradictory results [e.g., *Marchal et al.*, 2002; *Kucera et al.*, 2005]. Historically, palaeoceanographical investigations have focussed on the reconstruction of sea-surface temperatures (SST), with much less attention paid to sea-surface salinities (SSS) despite their critical role in controlling the thermohaline oceanic budget [e.g., *Seidov and Haupt*, 2003; *Curry et al.*, 2003; *de Verdière and Te Raa*, 2010]. One of the first successful attempt to reconstruct SSS was undertaken using $\delta^{18}$O data from planktonic foraminifera [e.g., *Shackleton and Opdyke*, 1973; *Thunell and Williams*, 1989; *Duplessy et al.*, 1992; *Maslin et al.*, 1995] but this approach remains controversial [*Rohling and Bigg*, 1998; *Schmidt*, 1999; *Rohling*, 2000; *LeGrande and Schmidt*, 2011]. Alternatively, SSS can be estimated from transfer functions *sensu lato* applied to microfossil assemblages. Until now only a few microfossil groups provide such evidence: among these are organic-walled dinoflagellate cysts (dinocysts [e.g., *de Vernal et al.*, 2005]).

[3] This paper reports on SSS estimations obtained on the reference core MD95-2002 [e.g., *Grousset et al.*, 2000; *Ménot et al.*, 2006] retrieved from the Celtic margin, a site which, during the Last Glacial Maximum (LGM), was located close to the outlet of the Manche paleoriver whose drainage network connected to the North-West (NW) European ice-sheets and rivers [e.g., *Lericolais et al.*, 2003, Figure 1]. Modelling exercises demonstrate that this site is ideally located to monitor the thermohaline evolution of the north-eastern Atlantic [e.g., *Roche et al.*, 2010; *Bigg et al.*, 2010]. Our focus is on the past 35 to 10 ka, a period known for its high amplitude climatic variability directly linked to the late Quaternary history of the northern hemisphere cryosphere. For the first time, two independent quantitative methods provide a robust reconstruction of the range of salinity changes which have affected the European temperate oceanic domain through time.

## 2. The Celtic Margin

[4] Core MD95-2002 (47.45°N, 8.53°W, −2174 m, Figure 1) was recovered on the Meriadzek Terrace, a topographic high presently dominated by hemipelagic sedimentation [*van Weering et al.*, 1998]. During the last glacial, the paleogeographical configuration of NW Europe (ice-sheets, sea-level low stand) enhanced the delivery of freshwater to the Celtic margin. In the area, this influence is typified by the occurrence of glacigenic materials contemporaneous with, or immediately pre-dating [e.g., *Grousset et al.*, 2000; *Scourse et al.*, 2000], Heinrich stadials (HSs) [e.g., *Heinrich*, 1988; *Sanchez-Goñi and Harrison*, 2010] and by laminated sedimentological fabrics interpreted to be the result of Terminations [e.g., *Zaragosi et al.*, 2001; *Mojtahid et al.*, 2005; *Peck et al.*, 2006; *Eynaud et al.*, 2007; *Penaud et al.*, 2009; *Toucanne et al.*, 2009, 2010].

## 3. Methods

### 3.1. Stratigraphy

[5] An updated age model of core MD95-2002, deriving from a polynomial regression (d°5) based on 19 $^{14}$C AMS

[1]EPOC, UMR 5805, Université Bordeaux 1, Talence, France.
[2]GEOTOP, Montreal, Quebec, Canada.
[3]School of Ocean Sciences, College of Natural Sciences, Bangor University, Anglesey, UK.
[4]Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette, France.
[5]Domaines Océaniques, UMR 6538, IUEM-UBO, Plouzané, France.
[6]Laboratoire Environnements Sédimentaires, IFREMER, Plouzané, France.

Corresponding author: F. Eynaud, EPOC, UMR 5805, Université Bordeaux 1, F-33400 Talence CEDEX, France. (f.eynaud@epoc.u-bordeaux1.fr)


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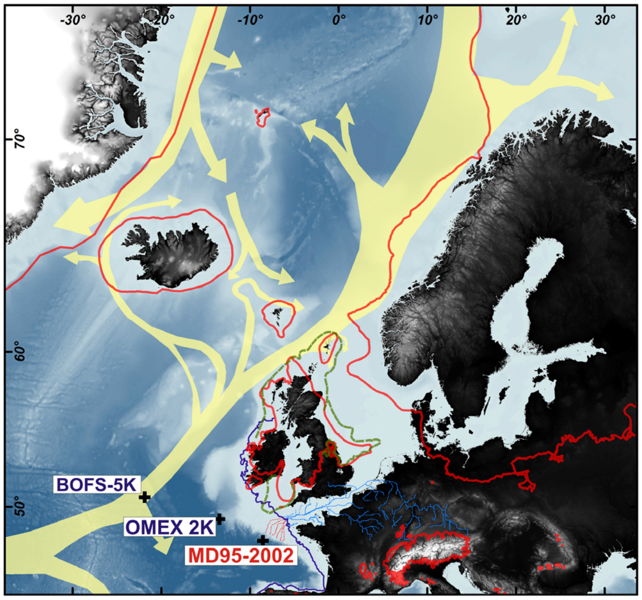


**Figure 1.** Location of core MD95-2002 and of cores cited in the paper. Modern North Atlantic major surface currents in yellow [after *Fogelqvist et al.*, 2003]; full glacial extension of the NH ice-sheets in red from *Grosswald and Hughes* [2002] and *Ehlers and Gibbard* [2004]; BIIS limits after modelling and compilation from *Boulton and Hagdorn* [2006] in green (dotted-line). Palaeo-coastline at 21 Ka BP in purple [after *Bourillet et al.*, 2003]; drainage system of the Manche paleoriver in cyan and pink [after *Lericolais et al.*, 2003].

dates over the first 30 ka (see section S1 of Text S1 in the auxiliary material), was published in *Ménot et al.* [2006] and *Eynaud et al.* [2007].[1] It was initially constructed using a 0.4 ka constant Marine Radiocarbon Reservoir Age Effect (MRE) [i.e., *Austin and Hibbert*, 2012]. Recent estimations of MRE in the area, derived from the tuning of relative abundances of the polar taxon *Neogloboquadrina pachyderma* left -*Np*l.-coiled to the $\delta^{18}$O ice-core record (either GISP2 or GRIP), have produced values up to 2 ka during major episodes of freshwater release [see *Peck et al.*, 2006; *Scourse et al.*, 2009; *Haapaniemi et al.*, 2010]. To test the coherency of our age model considering local MRE effects, we thus conducted a similar approach, tuning *Np*l abundances (Figure 2) to the NGRIP- $\delta^{18}$O (GICC05-1950 age scale [*Svensson et al.*, 2008]) considered as the regional stratotype for the North Atlantic (NA) region [i.e., *Austin and Hibbert*, 2012; *Austin et al.*, 2012]. This allowed us to generate eight new tie-points but does not change the initial age model regression equation sufficiently to justify a revision (see our arguments in Figure S1 in Text S1). Taking advantages of the recent discussion cautioning "marine event-based chronostratigraphies" [*Austin and Hibbert*, 2012], especially regarding phasing issues, we thus prefer to avoid any artificial tuning to the Greenland ice-cores. This approach thus generated a fully independent chronology. However, MRE potential effects on our stratigraphy are indicated in figures by the plot of the age difference through time obtained by the comparison of the tuned and non tuned age scales. It is important to note that the 14–10 ka period, not discussed in detail in the present paper, displays large MRE values. For this part of the record the age-model should probably be revised.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL052100.

### 3.2. Paleo-salinity Reconstructions

[6] Two independent methods were used for SSS reconstructions from core MD95-2002 (see sections S2–S4 of Text S1 for detailed explanations). The first combines stable isotope measurements ($\delta^{18}$O) on planktonic foraminifera shells and transfer function derived SST from foraminifera assemblages (thus based on calcareous/zooplanktonic >150 $\mu$m microfossils). For this work, original $\delta^{18}$O measurements (from monospecific subsamples of *Globigerina bulloides* and *Np*1. [see *Auffret et al.*, 2002]) were reconsidered and combined with new high resolution SST reconstructions between 35 and 10 ka (section S2 of Text S1). We also reviewed the methodology to estimate SSS by considering new calibrations of the salinity-water isotope relationship [e.g., *LeGrande and Schmidt*, 2011].

[7] The second method is based on the Modern Analogue Techniques (MAT) applied to dinocyst assemblages (organic/phytoplanktonic <150 $\mu$m microfossils) to directly estimate SSS [e.g., *Guiot and de Vernal*, 2007, see Appendix S3.2]. These two independent approaches allowed us to reconstruct SSS with error bars of $\pm$1.3 psu for $\delta^{18}$O / foraminifera derived results, and of $\pm$0.63 psu for dinocyst derived ones (in the >30 psu salinity domain). In addition to these reconstructions, sedimentological, biogeochemical and micropaleontological qualitative indicators of freshwater input have been compiled (section S4 of Text S1).

## 4. Results and Discussion

### 4.1. The Significance of Salinity Anomalies Along the Celtic Margin

[8] SSS estimates derived from $\delta^{18}$O / foraminifera and dinocyst assemblages yield coherent results with similar changes in both amplitude (see Table S1 in Text S1) and timing (Figure 2). In the northern Bay of Biscay, significant salinity decreases are synchronous with HSs, with SSS negative anomalies approaching 3 to 4 psu in surface waters. Such anomalies are 1 to 2 units greater (considering errors) than those estimated from central NA cores (BOFS-5K, 50°41′N, 21°52′W [i.e., *Maslin et al.*, 1995]; SU9003, 40°03′N, 32°00′W [i.e., *Chapman and Maslin*, 1999]). The data therefore illustrate the proximal meltwater signal from the outlet of the Manche paleoriver and dilution of this signal towards the central NA. SSS variations are associated with evidence for the delivery of fluvial and glacial material and feature a multi-step scenario for each HSs (Figure 2). The largest SSS offsets (>2 psu) within HS2 and HS1 coincide with the highest flux of Laurentide-sourced ice-rafted detritus (i.e., at ~24 ka and ~16.5 ka, respectively [after *Grousset et al.*, 2000; *Auffret et al.*, 2002]). This conversely suggests late and local melting of icebergs from distal Northeast American sources during these specific intervals.

[9] Though the two approaches show a high coherency in SSS events through time, it should be noted that absolute SSS values derived from the dinocyst data are lower than those derived from the foraminiferal data (saline excursions exceeding modern values by 2 units are reconstructed on the

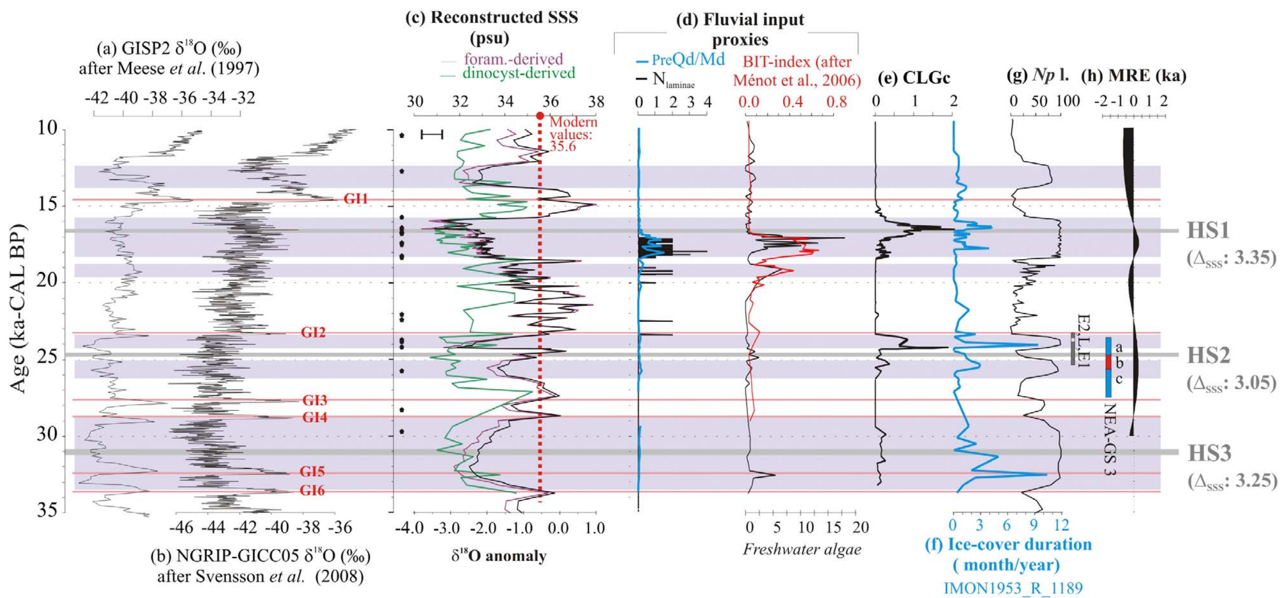


**Figure 2.** Comparison of the (a) GISP2 and (b) NGRIP GICC05 $\delta^{18}$O records to a compiled data set from core MD95-2002 over the past 35 to 10 ka, with: (c) SSS reconstructions derived from $\delta^{18}$O/ planktonic foraminifera data and from dinocysts (1 psu mean error bar) compared to modern local SSS (extracted with http://www.geo.uni-bremen.de/geomod/staff/csn/woasample.html); (d) fluvial input proxies including: PreQd/Md, the ratio of Pre-Quaternary versus Modern dinocysts; $N_{laminae}$, the number of laminae per cm of sediment; the branched and isoprenoid tetraether (BIT)-index data; the freshwater algae *Pediastrum* sp. concentration in the sediment (x$10^2$ nb. of colonies/ $cm^3$ of dry sed.); (e) CLGc: coarse lithic grain concentrations ($10^3$ grain/g dry sed.); (f) the dinocyst derived sea- ice-cover duration (g) relative abundances of *Neogloboquadrina pachyderma* left coiled (*Np*l.); (h) MRE, estimation of the marine reservoir age effect over the MD95-2002 site (see methods). Purple bands: periods for which both dinocyst and foraminifera derived SSS converge to indicate a SSS anomaly >2 psu (compare to modern values). Grey bars: HS mid-ages [*Thouveny et al.*, 2000] and their associated values of $\Delta_{SSS}$, i.e., mean SSS anomalies calculated as the difference between modern values and the mean SSS values during HSs (see Table S1 in Text S1). Red lines: Greenland interstadial (GI) warmings [after *Wolff et al.*, 2010]. Black dots: radiocarbon ages. E1, L, E2 = European (E) versus Laurentide (L) phases within HS2 in core MD95-2002 after *Grousset et al.* [2000]; NEA-GS3a,b,c = event stratigraphy of North East Atlantic Greenland Stadial 3 after *Austin et al.* [2012].

basis of planktonic foraminifera). Several factors could explain the discrepancies: among them, are artefacts linked to the methods themselves (i.e., the coherency of modern databases, the time and space dependent $\delta^{18}O_{SW}$-SSS relationship, $\delta^{18}$O biases in calcified foraminifera shells [e.g., *Hodell and Curtis*, 2008] (see section S3 of Text S1)) and differences in ecological strategies between the respective populations of planktonic foraminifera and dinoflagellates. Concerning the latter, the question of the depth habitat is probably the most significant since the two communities do not inhabit the same water depths. Dinoflagellates preferentially occupy the topmost fifty meters whereas foraminifera thrive at different water depths. The polar species *Np*l., is known to live at or below the pycnocline, notably at sites where low salinities characterize the surface layer [e.g., *Simstich et al.*, 2003; *Jonkers et al.*, 2010]. Therefore, SSS estimates from the isotopic composition of *Np*l. are likely related to mesopelagic conditions rather than carrying a surface signal. Larger differences in estimates between dinocysts and planktonic foraminifera may thus reflect a strong stratification of the water column. However, in polar-subpolar environments where sea-ice cover formation is associated with the rejection of brine, the low sea-surface salinity signal is transferred deeper into the subsurface layer [e.g., *Hillaire-Marcel and de Vernal*, 2008]. Thus, conversely, convergent low SSS values, as especially observed during HSs, could indicate freezing conditions. This is supported by the sea-ice cover duration reconstructed from dinocysts in addition to high iceberg density indices at that time. During HSs, alternative (or additional) processes could also explain the convergence of SSS reconstructions, including those promoting a mixing of the upper water layer: i.e., turbulent mixing in response to strong winds (modern winters in the Bay of Biscay generate a mixing of the upper 400–600 m of the water column [e.g., *Somavilla et al.*, 2009]) or/and iceberg drift [e.g., *Sancetta*, 1992; *Helly et al.*, 2011].

### 4.2. Paleo-salinity Millennial Scale Variability During the LGM (*Sensu Lato*)

[10] Over the interval encompassing HS2 to HS1 (~26 to 15 ka), the SSS record derived from foraminifera offers a high mean time resolution. It provides an excellent opportunity to discuss sub-millennial SSS oscillations during the LGM (Figure 3) and their connection with the Northern Hemisphere (NH) climatic variability. Actually, the LGM interval apart from HS1 and HS2 can be considered an interval in which the radiocarbon marine reservoir effect is reduced, due to the "relative" stability of the NH ice-sheets

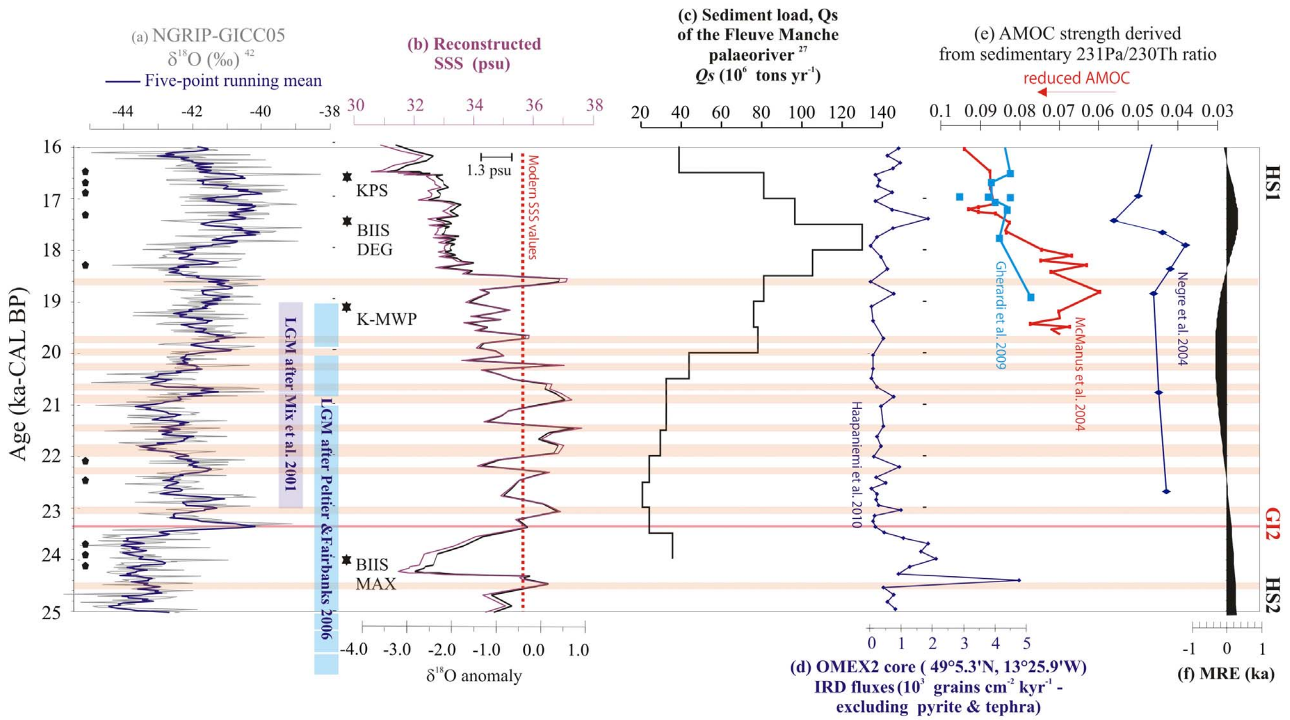


**Figure 3.** Comparison over the 25 to 16 ka interval of the: (a) NGRIP GICC05 $\delta^{18}$O record with (b) foraminifera-derived SSS in the Bay of Biscay and indicators of the (c, d) European ice-sheet dynamics and (e) AMOC strength derived from sedimentary $^{231}$Pa/$^{230}$Th ratio in the Atlantic sediment cores: OCE326-GGC5 (in orange, 33°42′N, 57°35′W; 4550 m water depth [after *McManus et al.*, 2004]), SU90-44 (in light blue, 50°01′N, 17°06′W, 4279 m water depth [*Gherardi et al.*, 2009]) and MD02-2594 (in dark blue, 34°42.64′S; 17°20′32E; 2440 m water depth [after *Negre et al.*, 2010]). (f) MRE, estimation of the marine reservoir age effect over the MD95-2002 site (see methods). Black dots: radiocarbon ages. GI2 warming after *Wolff et al.* [2010]. Stars locate terrestrial events of the BIIS history, with, BIIS-MAX: maximum BIIS extension [*Scourse et al.*, 2009]; BIIS–DEG: BIIS extensive deglaciation [*Bowen et al.*, 2002]; K-MWP: Kilkeel meltwater pulse [*Clark et al.*, 2004]; KPS: Killard Point stadial [*McCabe et al.*, 2005]. Note that the age model for OMEX2 is based on tuning of *Np*l. frequencies on GISP2 [*Haapaniemi et al.*, 2010].

(and especially the proximal BIIS), with no major events of freshwater advection known before 20 ka [e.g., *Clark et al.*, 2004]. This stability is also supported by reconstructions obtained at that time in the same area on the Manche paleoriver sediment load [e.g., *Toucanne et al.*, 2010] and from our data MRE calculation (Figure 3). Furthermore, the decision not to tune our age scale to Greenland records prevents circular reasoning in this case.

[11] As a whole, the LGM interval registers high SSS, comparable to modern values. Several short-lived low salinity pulses punctuate the sequence, but none of these reach the low SSS values characteristic of HSs. SSS oscillations detected at that time do resemble the variability detected in Greenland records. High SSS values match well high $\delta^{18}$O peaks in the NGRIP record [*Svensson et al.*, 2008], thus suggesting (within dating uncertainties <500 years), a direct link between interstadial conditions over Greenland and the occurrence of "normal" SSS values in the northern Bay of Biscay. Such high SSS could be interpreted as signalling conditions favourable to convection (close to those of the modern state), thus highlighting the coupling between the AMOC and the prevalence of mild climate at NW European latitudes. This provides supporting evidence that, in spite of the maximum extension of polar ice-caps, the glacial NA Ocean was in phase with atmospheric temperatures over Greenland. The link lies probably in the geographical location or extension of the Greenland main moisture sources at that time, as seen from ice-core records themselves [e.g., *Masson-Delmotte et al.*, 2005; *Jouzel et al.*, 2005]. These rapid climatic oscillations, similarly recorded in ice and marine LGM archives, thus reflect the expression of an ocean dynamically coupled to both ice and atmospheric systems.

[12] A low salinity event accompanied by a large input of fluvial-sourced materials is recorded between 20 and 19 ka BP prior to the large SSS depletion of HS1 (Figures 2 and 3). This event is contemporaneous of the Kilkeel meltwater pulse (K-MWP), recorded along the Irish coast [*Clark et al.*, 2004], though this is not registered by an IRD spike along the margin [*Scourse et al.*, 2009]. This low salinity event is followed by a short (within less than 500 years) resumption of high SSS then interrupted by the massive HS1. AMOC strength proxies document in parallel a major shift in its abyssal flow vigour [*McManus et al.*, 2004; *Gherardi et al.*, 2009], revealing a net decrease possibly accompanied by a change in the contribution of the southern deep component [*Negre et al.*, 2010]. This suggests strong intra- and inter-hemispheric teleconnections even in the case of a localised freshwater event (as the K-MWP) and supports modelling

simulations suggesting that the Celtic margin constitutes one of the nodal points for NA ocean convection dynamics over millennial time scale [*Roche et al.*, 2010].

## 5. Conclusion

[13] We used two independent analytical methods for reconstructing past SSS over the last 35 to 10 ka adjacent to the Manche paleoriver outlet. The coherence of the reconstructions in the amplitude and timing of paleosalinity changes is high. Detected oscillations highlight the coupled response of the surface ocean to the glacial/deglacial history in the Northern Hemisphere. The largest SSS excursions are recorded during HSs, with values as low as 30 in surface waters, which demonstrate the importance of meltwater discharges on the eastern side of the NA basin. Rapid increase of SSS immediately followed the freshwater pulses, illustrating the high sensitivity and low inertia of the ocean in glacial mode, thus supporting results from modelling simulations. This work clearly illustrates the relationships existing between oceanic, atmospheric and cryospheric systems both at regional and hemispherical scales.

[14] **Acknowledgments.** Core MD95-2002 was recovered thanks to financial support from MENRT, CNRS, IPEV and European Union MAST programme ENAM2. This work was supported by the French projects: ANR IDEGLACE, INSU LEFE/EVE RISCC, ARTEMIS $^{14}$C facilities, and has received funding from the European Union's Seventh Framework programme (FP7/2007–2013) under grant 243908, "Past4Future.Climate change-Learning from the past climate." (This is Past4Future contribution 21). JDS acknowledges the support of the Climate Change Consortium of Wales (C3W). This is an UMR/EPOC 5805 (Bordeaux Univ./CNRS) contribution 1865.

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